NSTX

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TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: GUIDELINES RELATED TO THE USE OF MAGNETIC MATERIALS ON NSTX

This memo presents a technical basis for a proposed set of guidelines related to the use of magnetic materials on NSTX.

Technical Overview

Ideally, the NSTX machine and all surrounding regions would have magnetic permeability μ equal to that of free space $\mu_o = 4\pi \times 10^{-7}$. In other words the relative magnetic permeability μ_r should equal 1.0 everywhere, and the magnetic susceptibility X ($\mu_r = 1 + X$) should equal zero. In practice this is not realizable because...

- materials used in the construction of the machine itself, which possess the necessary mechanical properties, include ferromagnetic materials and do not possess perfectly "non-magnetic" ($\mu_r = 1.0$) properties (e.g. stainless steel alloys and associated welds);

- various features of the facility infrastructure include ferromagnetic materials (e.g. steel I-beams and rebar in the walls and floor);

- various components associated with the operation of the machine include ferromagnetic materials (e.g. motors, transformers, solenoid actuators, etc.).

These "magnetic" materials ($\mu_r > 1.0$) distort the field compared that which would result from currents flowing in the NSTX magnets, passive structure, and plasma if they were not present. This distortion results from...

- compression of flux from the external applied field in the volume of the magnetic materials;

- remnant flux originating from the ferromagnetic materials themselves, due to their history of magnetization.

A rigorous analysis of the distortion of the field with magnetic materials present is difficult. A simplified method which can be used as an approximation to bracket the problem is based on the assumption that the field B in the volume of the magnetic material is equal to μ_r times the applied field which would be present in the ideal non-magnetic environment...

$$B = \mu_r * \mu_0 * H = \mu_r * B_0$$

subject to the constraint that saturation will occur at some level (as high as ≈ 2T for pure iron). Then, the error field some distance away can be computed by representing the magnetized volume by an equivalent surface current distribution which produces a field B_m representing the magnetization within the volume, equal to the difference between the assumed field and the ideal field ($B_m=B-B_0=B_0*(\mu_r-1)$). For example a permanent rod magnet can be represented by a solenoid, and the effect of a rod of magnetic material immersed in an applied field can be represented by a solenoid with an internal field equal to μ_r-1 times the applied field. In case the point of interest is far away compared to the dimensions of the magnetized volume then the field at a distance may be approximated based on the total magnetic dipole moment of the volume, equal to B_m*V_m, where V_m is the magnetized volume. In spherical coordinates the field at distant points from a magnetic dipole, with its axis in the azimuthal direction ($\theta=0^o$) and its median plane on the origin consists of B_r and B_θ components as follows....

$$B_r = 2B_mV_m/4\pi r^3\sin\theta$$

$$B_\theta = B_mV_m/4\pi r^3\cos\theta$$

Therefore at distant points on axis ($\theta=0^o$) $B_r = 2B_mV_m/4\pi r^3$ and $B_\theta = 0$, and at distant points in the median plane ($\theta=90^o$) $B_r = 0$ and $B_\theta = B_mV_m/4\pi r^3$.

In addition to the above, additional sources of "field errors" include coil misalignments, coil turn to turn transitions, structure misalignments, bus conductors, etc.. The net "error field" is the difference between the actual field, as determined by all of the sources of error, and the ideal field. What matters is the error field within and immediately surrounding the vacuum vessel. Possible deleterious effects include....

- stray vertical and radial fields at the breakdown null target point

- plasma instabilities (e.g. locked modes)

- local distortion of plasma shape leading to increased local dissipation on PFCs

- errors in magnetic diagnostics

Over any defined surface (e.g. the q=2 flux surface) 3-d error field can be decomposed into a double Fourier series consisting of poloidal (m) and toroidal (n) harmonics. Axisymmetric (n=0) error field components B_r and B_z, assuming that they are small, can be compensated for, at least at a single r,z location, using the PF coils since bipolar and up/down asymmeric current control is being provided. For this reason it can be argued that stray axisymmetric fields at breakdown are not an issue, assuming that the time response of the current control is adequate. In the current NSTX baseline, field error correction coils are not provided so there is no mechanism for compensating for non-axisymmetric ($n\neq0$) field errors. Also, there is no mechanism for compensating for $B_ø$ (errors in the toroidal direction) for any n number. Therefore the non-axisymmetric poloidal field errors and the toroidal field errors are of primary concern.

For the poloidal field the main physics concern (related to locked mode avoidance) is the m=2, n=1 component of the radial field normal to the q=2 flux surface, for which the limit (from all sources) shall be ≤ 5 gauss. C. Kessel has analyzed the 2,1 errors due to PF coil misalignments[1]. Short of a complete Fourier decomposition, the maximum value of any m,n component of an error field can be bracketed by taking the maximum error field on the surface of interest and applying a factor[2]...

$$k = 16/m/n/\pi^2$$

which is the limit on the magnitude of any component of the Fourier spectrum, e.g. for m=2,n=1 the maximum value of the component will be 0.81 times the maximum error.

For the toroidal field the main physics concern is the spatial ripple, for which the peak-to-average toroidal field ripple shall be ≤ 0.5% over the entire plasma cross section. The discrete nature of the outer legs is the dominating factor in this regard, but additional error sources will contribute to a small degree.

The evaluation of any individual source of field error in isolation is insufficient to determine its acceptability even if an allowable is set for the net error field, because the net effect of all error sources must be considered. The geometric distribution of all sources must be considered in order to determine the net 3d error field. For example, two sources of equal error might be geometrically positioned such that they cancel out. One could approach the problem from a statistical angle (e.g. Monte Carlo analysis) but for NSTX a simplified set of rules and allowances is sought.

TFTR Practice

During the design phase (1978) TFTR evaluated the effect of vacuum vessel welds with $\mu_r > 1$ in terms of toroidal field perturbation[3]. The approach was to analyze, as a function of applied field, one 1/20 (18°) segment in isolation and determine, based on the composite of the toroidally directed welds at various locations, the allowable weld μ_r such that the maximum field error at the plasma surface would be less than a given allowable. For 1T at the weld and 10G error at the plasma edge the μ_r allowable was found to be 1.29. The writer did not pursue data as to the actual as-built weld permeability on TFTR.

At the beginning of operations (1983) TFTR established an initial inventory of magnetic materials ($\mu_r > 10$) around the machine and published data concerning maximum field error at the breakdown null target as a function of toroidal angle[4]. The direction of the error field was not specified. The writer supposes that this data was computed using the formula for maximum field on axis from a magnetic dipole ($2B_mV_m/4\pi r^3$), and the volume of each inventory item and radius from the point of interest was considered and all of the contributions were summed. The extent of assumed magnetization is not mentioned but the writer supposes that a value of 1T was taken based on the saturation of iron.

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[1] 97-1108-PPPL-CKESSEL-01, "PF Coil Error Fields in NSTX"

[2] R Woolley

[3] PE-M-2849, "Toroidal Field Perturbation due to Magnetically Permeable Vacuum Vessel Welds", D. WeissenbuRger, 8/9/78

[4] TFTR Magnetics Handbook, section 4.3.1, 1983

Later on, TFTR established rules for introduction of additional ferromagnetic materials into the test cell[5]. Three spherical zones were established with respect to the machine center at r=0, z=0. A fourth zone was established to cover the remainder of the test cell, test cell basement, and DARM. Limits on the total allowable mass in each zone were established by setting an allowable error field contribution, from each zone, measured at r=0, z=0, of 5 gauss, based on the following assumptions...

- all material assumed magnetized at 1T

- all material assumed lumped at a single location at the mean radius of the zone, and aligned such that the worst case error field would result based on the equation for field on axis at points remote from a magnetic dipole ($B = 2B_mV_m/4\pi r^3$)

The total allowable mass of additional materials was noted to be less than 50% of the material already present in the building structure, which was "grandfathered".

Three categories for approval for introduction of new materials were established, on the basis that, ultimately, the number of installations in each category would result in the total allowable mass established for each zone. Only materials with μr greater than a minimum specified value were considered.

			Mass Limit (lb.) for Category		
Zone	Radius (ft.)	Min. μr to be considered	A (max. 1000 items)	B (max. 50 items)	C (max. 10 items)
1	0-20	1.05	-	-	All items
2	20-35	2	<10	10-200	>200
3	35-55	2	<50	50-1000	>1000
4	Other TC, TCB, DARM	2	<200	200-4000	>4000

Additionally, the criteria set forth is such that, based on the TFTR stray field, outside of zone 1, the magnetic forces are less than the weight of the material (#force/#weight < 1).

The selection of the 5G allowable for each zone as measured at r=0,z=0 is somewhat arbitrary, but nevertheless provides a means for establishing guidelines. The assumption that the material is lumped in each zone is reasonable because the stray fields which magnetize the objects are axisymmetic and miplane symmetic, albiet not perfectly spherical, in which case any object, no matter its location around the sphere, would cause the same field error at the center. The assumption concerning magnetization of objects at 1T is increasingly conservative as one moves away from the machine center. On the other hand for objects with high iron content ($\mu_r \approx 1000$) the flux compression will be significant.

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[5] "Magnetic Materials in TFTR", R. Hawryluk, 2/12/85

TFTR also issued, in 1991, a "Specification for Magnetic Permeability Requirements and Testing"[6] in which allowables for μ_r were specified for materials to be used in the machine proper as follows...

- base material $\mu_r \leq 1.02$

- worked material $\mu_r \leq 1.05$

- welds $\mu_r \leq 1.20$

According to recent NSTX experience the above levels are impractical and a more reasonable set of allowables which will exclude gross misapplication of materials while avoiding procurement/fabrication problems and cost impacts is as follows...

- base material $\mu_r \leq 1.05$

- worked material $\mu_r \leq 1.1$

- welds $\mu_r \leq 1.70$

The quantitative impact of these allowables in terms of field error on NSTX needs to be assessed.

Evaluation of Known NSTX Error Field Sources

1. PF Coil Misalignments

Error fields from PF coil misalignments (m=2,n=1 components of field normal to q=2 flux surface) were analyzed by C. Kessel[1]. His results, expressed in terms of error per mm based on his results at dr=3mm and tilt of 0.2° are summarized in the following table.

PF Coil	dB/dr	dB/dø (tilt)	dB/dz (tilt)
	(gauss/mm)	(gauss/deg)	(gauss/mm)
1	0.046	0.295	0.094
2	0.097	0.590	0.042
3	0.190	4.215	0.162
4	0.092	5.195	0.166

Assuming that the accuracy of the coil construction and their placement is good to a few mm, all of the numbers are well below the allowable of 5 gauss, but the net composite effect is unknown. As a point of reference, assuming that all of the errors are additive for both the upper and lower coils, a consistent 1mm error in r and z for each coil results in a total error sum of ≈ 6 gauss.

2. Other Coil Error Sources

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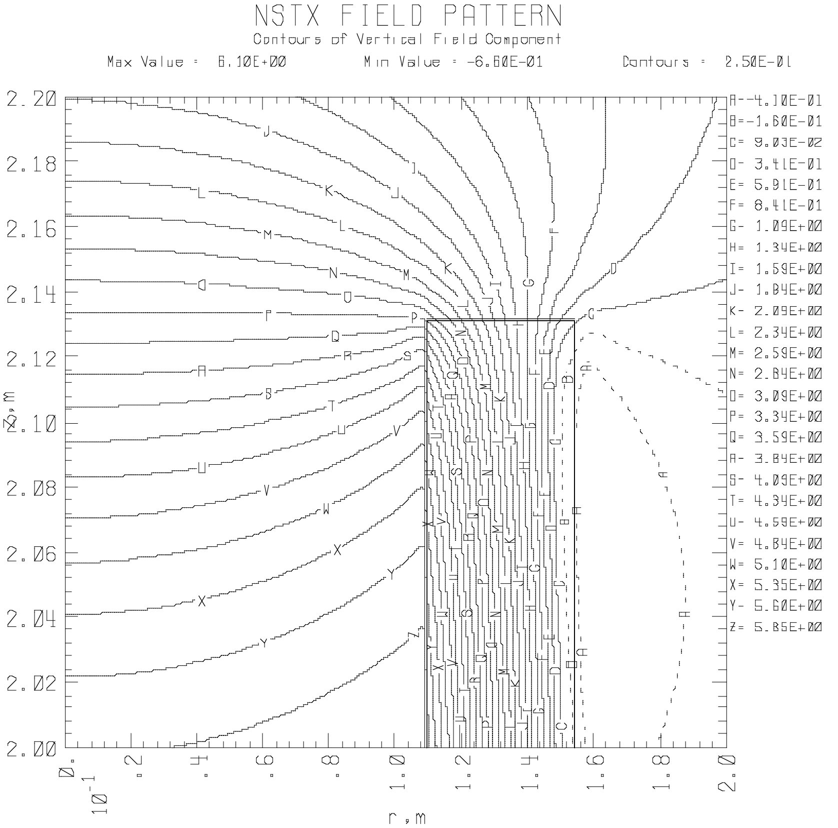
[6] SPEC-ICRF-KN01, "Specification for Magnetic Permeability Requirements and Testing", S Raftopoulos. 3/21/91

Error fields from TF coil misalignments, PF/OH/TF coil turn to turn transitions, and bus bars have not yet been quantified.

3. I-beams

4. Center Stack Weldments

Various welds join the various cylinders associated with the center stack to their flanges. Probably the most significant of these is the weld which joins the OH tension tube to its flanges, because it is in a high field region (just inside the bore of the OH coil there is a strong vertical field). The approximate cross sectional area of the weld is $0.25^2/2 = 0.031$ square inches (the weld is triangular in cross section with two sides approximately 1/4". The diameter is equal to the bore of the OH coil ≈ 8.6". Contours of the vertical field in the bore of the OH coil is shown in shown in the following figure. At the end of the coil just inside the bore the field is ≈ 3.4T.



Assuming that the weld material will saturate at 2T, then since the magnetizing field $B_m = B_0 * (\mu_r - 1)$, saturation will occur in a 3.4T field as long as $\mu_r \geq B_m/B_0 + 1 = 2/3.4 + 1 = 1.59$, which is likely. So, saturation at 2T is assumed. The weld is located ≈ 2m above the midplane. Using the formula for the field on axis at points distant from a magnetic dipole, the maximum error fields are calculated as follows.

CSA	0.03125	in^2
Diameter	8.6	in
Circumference	27.02	in
Volume	0.84	in^3
	1.38E-05	m^3
Saturation Field	2.00	T
Z	2.00	m
Midplane (z=0) Error	5.51E-07	T
	0.006	G
Plasma Edge (z=1.3m) Error	1.28E-05	T
	0.128	G

These error fields are ignorable because their magnitudes are insignificant. Also it is axisymmetric and can be compensated for during plasma breakdown. As points of reference the stray field from the OH at the field null target on the midplane at breakdown, which is compensated for by PF3, is ≈ 100G, and the fields at the plasma edge are in the range of ≈ 1T.

Other similar welds exist on the flanges of the center stack casing at the transition between the stepped cylinders and at the ends of the casing, where the field is much lower.

Additional welds exist in the hub assembly. Some of these are not toroidally continuous, so that their error contributions would be non-axisymmetric.

As a point of reference, assuming 2m distance from the midplane, the amount of weld material saturated at 2T which would yield 0.1G error at the midplane is ≈ 15 in^3, which corresponds to 480 inches (40') of weld assuming a weld cross section of 0.03125 in^2.

5. Center Stack Annular Flanges

Annular flanges at the top and bottom of the OH tension tube are exposed to the magnetic cc:

J Chrzanowski
P Heitzenroeder
F Malinowski
T Meighan
M Ono

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